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Abstract: **PURPOSE** The aim of this study was to evaluate the efficiency and performance of different fat suppression techniques for clinical 7 T knee magnetic resonance imaging including the slice-selective gradient reversal (SSGR) technique. **MATERIALS AND METHODS** This article is an ethical board-approved prospective study with written informed consent from 8 volunteers (mean, 31 ± 4 years). It included fat phantom and knee magnetic resonance imaging at 3 T (Magnetom Skyra; Siemens Healthcare) and at 7 T (Achieva, Philips Healthcare). At 3 T, an axial proton density-weighted turbo spin echo sequence with spectral adiabatic inversion recovery (SPAIR) was acquired. At 7 T, a series of 5 proton density-weighted turbo spin echo sequences was acquired: (a) without fat suppression, (b) with spectral presaturation with inversion recovery (SPIR), (c) with SPAIR, (d) with SSGR, and (e) with the combination of SSGR + SPIR. Additional noise scans allowed pixelwise calculation of signal-to-noise ratio and contrast-to-noise ratio maps. Quantitative data at 7 T were compared with each other but not to 3 T. Two independent radiologists evaluated overall image quality, homogeneity and grade of fat suppression, and the delineation between 2 adjacent structures. Results were compared using Wilcoxon signed rank and paired sample t tests. **RESULTS** Relative signal-to-noise ratios of fat demonstrated that the SPIR technique reduced the fat signal to $45\% \pm 5.4\%$; SPAIR, $18\% \pm 1.2\%$; SSGR, $14\% \pm 1.1\%$; and SSGR + SPIR, $11\% \pm 0.3\%$. Contrast-to-noise ratio showed superior contrast between muscle-fat ($P < 0.001$) and fluid-fat ($P = 0.001$) for SSGR and SSGR + SPIR. The radiologists rated the overall image quality higher at 7 T than 3 T. The homogeneity and grade of fat suppression as well as the delineation between 2 different (adjacent) structures were rated best for SSGR + SPIR. **CONCLUSIONS** At 7 T, fat saturation for clinical knee imaging using SSGR and the combination of SSGR + SPIR was superior compared with standard methods based on spectrally selective radiofrequency pulses.

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Clinical Magnetic Resonance Imaging of the Knee at 7 T

Optimization of Fat Suppression

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Purpose: The aim of this study was to evaluate the efficiency and performance of different fat suppression techniques for clinical 7 T knee magnetic resonance imaging including the slice-selective gradient reversal (SSGR) technique.

Materials and Methods: This article is an ethical board–approved prospective study with written informed consent from 8 volunteers (mean, 31 ± 4 years). It included fat phantom and knee magnetic resonance imaging at 3 T (Magnetom Skyra; Siemens Healthcare) and at 7 T (Achieva, Philips Healthcare). At 3 T, an axial proton density-weighted turbo spin echo sequence with spectral adiabatic inversion recovery (SPAIR) was acquired. At 7 T, a series of 5 proton density-weighted turbo spin echo sequences was acquired: (a) without fat suppression, (b) with spectral presaturation with inversion recovery (SPIR), (c) with SPAIR, (d) with SSGR, and (e) with the combination of SSGR + SPIR. Additional noise scans allowed pixelwise calculation of signal-to-noise ratio and contrast-to-noise ratio maps. Quantitative data at 7 T were compared with each other but not to 3 T. Two independent radiologists evaluated overall image quality, homogeneity and grade of fat suppression, and the delineation between 2 adjacent structures. Results were compared using Wilcoxon signed rank and paired sample *t* tests.

Results: Relative signal-to-noise ratios of fat demonstrated that the SPIR technique reduced the fat signal to $45\% \pm 5.4\%$; SPAIR, $18\% \pm 1.2\%$; SSGR, $14\% \pm 1.1\%$; and SSGR + SPIR, $11\% \pm 0.3\%$. Contrast-to-noise ratio showed superior contrast between muscle-fat ($P < 0.001$) and fluid-fat ($P \leq 0.001$) for SSGR and SSGR + SPIR. The radiologists rated the overall image quality higher at 7 T than 3 T. The homogeneity and grade of fat suppression as well as the delineation between 2 different (adjacent) structures were rated best for SSGR + SPIR.

Conclusions: At 7 T, fat saturation for clinical knee imaging using SSGR and the combination of SSGR + SPIR was superior compared with standard methods based on spectrally selective radiofrequency pulses.

Key Words: magnetic resonance imaging, fat suppression, high-field imaging, knee, 7 T

(Invest Radiol 2018;00: 00–00)

The knee is the most commonly injured joint in adults. In the United States, an estimated 2.5 million mostly sports-related knee injuries are counted in emergency departments¹ and the annual consulting rate in primary care practices in the United Kingdom for knee injuries is 32 per 1000 patient-years.² Magnetic resonance imaging (MRI) is the modality of choice to evaluate internal derangements.³ Although comprehensive data on its current use is rare, older studies have shown that knee MRIs were performed at the rate of 3.4 in 1995 in the United States⁴ and 15.6 per 1000 person-years in Norway in 2004.⁵ This rapid

increase in use has been driven by the advances in MRI scan quality over the past years but, at the same time, has otherwise also stimulated further technical improvements including the use of higher-field strengths, dedicated coils, and sequences.

Recently, dedicated knee coils have become available for 7 T systems, and several groups are now exploiting the potential of knee imaging at ultra-high-field strength in terms of general sequence or imaging optimization^{6–10} or dedicated applications, for example, cartilage imaging.^{8,11–13} Magnetic resonance imaging at 7 T has several inherent challenges. The most important and mandatory one for musculoskeletal imaging is fat suppression.¹⁴ In our experience, we found it very difficult to produce clinically useful 7 T knee MRI scans that satisfied our expectations in terms of robust fat suppression usable for clinical routine.

Fat suppression at 7 T should in theory benefit from the larger frequency difference between water and fat (7 T, 1000 Hz; 3 T, 440 Hz; 1.5 T, 220 Hz).¹⁴ However, reliable fat suppression is challenging due to increased magnetic field inhomogeneity, inhomogeneous radiofrequency (RF) transmit field, and limitations of the specific absorption rate (SAR). Especially, fat suppression in combination with turbo spin echo sequences suffers from the latter two issues. Methods based on spectrally selective RF pulses such as spectral presaturation with inversion recovery (SPIR) or spectral adiabatic inversion recovery (SPAIR) increase SAR and will lengthen the acquisition time.¹⁴ Thus, alternatives are needed to improve fat saturation. Such an alternative is slice selective gradient reversal (SSGR) technique presented by Nagy et al,¹⁵ which uses gradients of opposing polarity for the excitation and the refocusing pulse. A detailed description of the technique is provided in the original report.¹⁵ This method has been shown to perform well at high-field strength and does not prolong scan time or increase SAR.^{15,16} Our hypothesis was that this technique can be used for improving fat suppression at 7 T to gather clinically usable and robust images of the knee.

Thus, the purpose of our prospective study was to evaluate quantitative and qualitatively the efficiency and performance of different fat suppression techniques for clinical 7 T knee MRI including the SSGR technique.

MATERIALS AND METHODS

This study included phantom measurements as well as imaging of human subjects. This was an investigator-driven study without support or any influence from the industry.

Study Subjects

This article is a prospective ethical board–approved study with written informed consent from 8 healthy volunteers ranging in age from 25 to 38 years (mean age, 31 ± 4 years, 2 women). Inclusion criteria were older than 18 years and no contraindication for MRI at 3 T and 7 T.¹⁷ Exclusion criteria were knee pain or prior knee surgery. Volunteers (1 left knee, 7 right knees) were imaged at 7 T (Achieva; Philips Healthcare, Best, the Netherlands) using a dedicated 28-channel TX-knee coil (QED; Quality Electrodynamics, Mayfield Village, OH) and at 3 T (Magnetom Skyra; Siemens Healthcare, Erlangen, Germany) using a 15-channel TX-knee coil (QED). To reduce susceptibility effects at tissue-air interfaces, soft cushions filled with Fomblin oil (200 mL and 400 mL; Solvay, Italy) were placed on top and around the patella

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at both field strengths.¹⁸ Legs were immobilized using sand bags and straps. Possible adverse effects of 3 T and 7 T imaging with respect to duration of the symptom, intensity, requirement for further treatment, and relationship to medical device were recorded.

Phantom

A dedicated water-fat phantom using ultrasonic gel and 100% pure swine fat (purchased in a grocery store) was manufactured. Both substances were filled into commercially available 150 mL plastic vials. To avoid artifacts from large air bubbles, the fat was carefully heated until it became fluid and centrifuged before it was filled into the vials. Subsequently, it was cooled down to room temperature (22°C) where it became semirigid. In addition, both vials were vacuumed to extract remaining air. The phantom was then positioned in the isocenter of the knee coil. All phantom measurements were performed at 7 T using this phantom (Fig. 1).

Magnetic Resonance Imaging

At 3 T, an axial proton density-weighted turbo spin echo sequence with SPAIR from the clinical standard protocol was acquired for qualitative analysis using a dedicated 15-channel TX-knee coil (QED). At 7 T, a series of 5 proton density-weighted turbo spin echo sequences were acquired for phantom measurements, for quantitative analysis, and for qualitative analysis: (a) without fat suppression, (b) with SPIR, (c) with SPAIR, (d) with SSGR, and (e) with the combination of SSGR + SPIR using a dedicated 28-channel TX-knee coil (QED). Except for the fat suppression technique, all other imaging parameters were kept identical for both field strengths and all acquisitions (field of view, 160 × 160 mm²; repetition time (TR), 3800 milliseconds; echo time (TE), 35 milliseconds; acquired in-plane resolution, 0.35 × 0.45 mm; slice thickness, 2.5 mm; 15 slices; 1 signal average; bandwidth, 216 Hz/pixel; acquisition time, 3:40 minutes). Because scanners were produced by different companies, care was taken to switch off any platform specific settings (eg, image filters). Each 7 T sequence contained an additional noise scan without gradients and RF to allow pixelwise calculation of signal-to-noise ratio (SNR) maps according to a previously published method.¹⁹

Quantitative Analysis

For the quantitative analysis of the phantom images, circular regions of interest (ROIs) were chosen (because the vials were round) to measure the signal from within the vials. To avoid artifacts from the plastic wall, ROIs were drawn slightly smaller than the vials diameter (diameter of the vials, 25 mm).

For quantitative analysis of the in vivo volunteer images, SNR values were extracted by the same reader from circular ROIs within the cartilage, bone marrow, joint fluid, muscle, and fat. Care was taken to avoid partial volume effects as well as to place the ROIs in identical anatomic regions in all 8 volunteers. Therefore, a section was chosen, which included the mid-level of the patella. Contrast-to-noise ratio (CNR) values were derived from the SNR results to evaluate tissue

contrast for muscle-fat, cartilage-fat, fluid-fat, fluid-cartilage, and cartilage-bone marrow using the following equation (eq):

$$(eq1) \text{ CNR} = \frac{S_1 - S_2}{\text{Noise}} = \text{SNR}_1 - \text{SNR}_2,$$

with CNR as contrast-to-noise ratio; S1, signal of tissue 1; and S2, signal of tissue 2.

All calculations and the quantitative analysis of SNR and CNR maps were performed by the same investigators (M.W., 20 years' experience with MRI research; A.M., 5 years' experience with MRI research) in consensus using in-house developed MATLAB routines (release 7.3; The MathWorks, Natick, MA).

Qualitative Analysis

All volunteer images were qualitatively analyzed by 2 fellowship trained radiologists (G.A., 15 years' clinical experience; M.M., 10 years' clinical experience) who were blinded to the volunteer details, field strength, and fat suppression technique of the images. Therefore, all images were transferred to a standard picture archive and communication (PACS) workstation (Impax 5.0; Agfa Healthcare, Germany) and displayed to them in a random order and with image annotations switched off. Both radiologists evaluated independently the overall image quality, the homogeneity of fat suppression, the grade of fat suppression, as well as the delineation between 2 different (adjacent) structures (Table 1) using 5-point Likert scales.²⁰ In addition, all artifacts, if present, were noted.

Statistical Analysis

Descriptive data were provided as frequencies and means with standard deviation. Interreader agreement for the qualitative evaluation was analyzed with Cohen kappa (κ) coefficient and interpreted according to Kundel and Polansky: 0.21–0.40, indicated fair; 0.41–0.60, moderate; 0.61–0.80, good; and >0.81, indicated excellent agreement.²¹ Quantitative and qualitative results from the different sequences were compared using paired sample *t* tests and Wilcoxon signed rank tests together with a correction for multiple testing using SPSS (v24.0, IBM Inc, Armonk, NY). A *P* value of less than 0.05 was considered statistically significant. Quantitative data at 7 T from both the phantom as well as the volunteers were only compared with each other but not to 3 T.

RESULTS

Adverse Effects

One of the 8 volunteers reported slight nausea and minor headache after imaging at 7 T. Symptoms were related to the field strength and were not related to the other devices. Symptoms resumed without treatment after few hours.

Quantitative Analysis

In the phantom experiment at 7 T, fat was only partially suppressed using SPIR and SPAIR. Slice-selective gradient reversal and SSGR + SPIR suppressed the fat signal better compared with the original fat signal

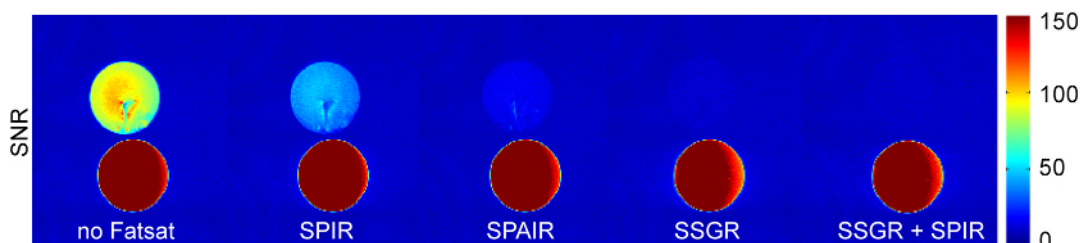


FIGURE 1. Signal-to-noise map of the phantom measured at 7 T. The upper row shows the vial with swine fat; the lower row shows the gel-filled vial.

TABLE 1. Evaluation Criteria for the Qualitative Analysis of Volunteer Images Using 5-Point Likert Scales

Image quality and artifacts	1 = nondiagnostic, full of artifacts; 2 = limited for diagnosis, severe artifacts; 3 = diagnostic but several artifacts; 4 = fully diagnostic despite some artifacts; 5 = fully diagnostic, no artifacts
Homogeneity of fat suppression	1 = absolutely inhomogeneous, not tolerable in clinical routine; 2 = very inhomogeneous, not tolerable; 3 = minor inhomogeneity, tolerable; 4 = homogenous, normal use in clinical routine; 5 = totally homogenous
Grade of fat suppression	1 = fat is not suppressed, not feasible for clinical use; 2 = low fat suppression but not feasible for clinical use; 3 = intermediate fat suppression, limited clinical use; 4 = good fat suppression, clinical useful; 5 = perfect fat suppression, ideal for clinical use
Delineation	1 = no delineation possible, no contrast between 2 structures; 2 = delineation possible but contrast very low between 2 structures; 3 = delineation possible with intermediate contrast between 2 structures; 4 = good delineation but contrast could be better between 2 structures; 5 = perfect delineation with high contrast between 2 structures
Fat vs muscle	
Cartilage vs fat	
Fluid vs fat	
Fluid vs cartilage	
Cartilage vs bone	
Cartilage vs cartilage	

without any suppression (below 15% of the original signal; Table 2; Figs. 1, 2). Relative SNRs of fat demonstrated that the SPIR technique reduced the fat signal to $45\% \pm 5.4\%$; SPAIR, $18\% \pm 1.2\%$; SSGR, $14\% \pm 1.1\%$; and SSGR + SPIR, $11\% \pm 0.3\%$. Figure 3 shows representative examples of acquired morphologic images in vivo of one volunteer at both field strengths, and Figure 4 shows corresponding SNR maps (Figs. 3, 4). At 7 T, SSGR and SSGR + SPIR yielded significantly lower SNR in fat and in fat containing bone marrow of the femur and patella (Fig. 5) compared with the differences found for SPIR and SPAIR. Both SSGR and SSGR + SPIR yielded significantly lower SNR in cartilage compared with SPIR ($P \leq 0.001$ and $P = 0.002$, respectively), but similar SNR compared with SPAIR (SSGR, $P = 0.105$; SSGR + SPIR, $P = 0.132$). Evaluation of CNR is illustrated in Figure 6, which indicates superior contrast for the SSGR and SSGR + SPIR methods (Fig. 6).

However, detailed statistical analysis revealed statistically significant superiority of SSGR and SSGR + SPIR only for muscle-fat and fluid-fat (Table 3). For cartilage-fat, fluid-cartilage, and cartilage-bone marrow, the “superiority” of SSGR was not consistently significant (Table 3).

Qualitative Analysis

The interreader agreement was excellent (Table 4). In vivo images showed improved overall image quality for all 7 T methods compared with the clinical reference 3 T SPAIR image (all $P \leq 0.001$; Table 4), which was mainly due to arterial pulsation artifacts, which were present in all 3 T images but less pronounced at 7 T. The grade of fat suppression, homogeneity of fat suppression, or the delineation of different structures was not affected by these pulsation artifacts. Compared with 3 T, the grade of fat suppression was rated lower for SPIR (mean \pm SD, 2.0 ± 0.00) and

TABLE 2. Quantitative Analysis of 7 T SNR Maps

A: Absolute SNRs of Tissue in the Knee for the Different Protocols at the 7 T Based on SNR Maps Generated Using Noise Scans										
	No Fatsat		SPIR		SPAIR		SSGR		SSGR + SPIR	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Cartilage	81.59	23.40	79.91	26.72	55.66	18.74	48.89	19.92	47.46	22.46
Fat	185.10	28.78	86.69	12.86	39.71	4.96	21.93	3.11	18.46	3.13
Femoral bone	130.33	27.13	46.43	5.85	24.96	4.82	16.02	2.98	14.03	4.23
Fluid	159.43	30.45	130.20	35.48	105.67	8.38	113.20	15.43	113.96	21.11
Muscle	101.41	16.81	94.07	17.57	66.85	12.54	84.17	13.99	82.95	12.72
Patellar bone	161.21	42.52	84.66	21.05	49.23	13.34	18.61	3.78	15.43	4.84

B: Statistical Analysis Using Paired Sample *t* Tests of Absolute SNR Value

	SPIR vs SPAIR	SPIR vs SSGR	SPIR vs SSGR + SPIR	SPAIR vs SSGR	SPAIR vs SSGR + SPIR	SSGR vs SSGR + SPIR
<i>P</i>						
Cartilage	≤ 0.001	≤ 0.001	0.002	0.105	0.132	0.652
Fat	≤ 0.001	≤ 0.001	≤ 0.001	0.000	≤ 0.001	0.061
Femoral bone	≤ 0.001	≤ 0.001	≤ 0.001	0.000	≤ 0.001	2.087
Fluid	0.109	0.323	0.381	0.124	0.221	0.828
Muscle	≤ 0.001	0.002	0.003	≤ 0.001	≤ 0.001	0.354
Patellar bone	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	0.004

P values of < 0.05 was considered statistically significant.

SNR indicates signal-to-noise ratio; SPIR, spectral presaturation with inversion recovery; SPAIR, spectral adiabatic inversion recovery; SSGR, slice-selective gradient reversal.



FIGURE 2. Bar charts showing signal-to-noise values in the phantom at 7 T normalized to the acquisition without fat suppression.

SPAIR (3.0 ± 0.00) but higher for SSGR (4.0 ± 0.25) and SSGR + SPIR (5.0 ± 0.00 ; Table 4, Figs. 3, 7). The homogeneity of the fat suppression was rated lower for 7 T SPIR (3.69 ± 0.48) compared with the clinical reference 3 T SPAIR image (3.94 ± 0.44). The homogeneity was better than the clinical reference image with 7 T SPAIR (4.0 ± 0.0), 7 T SSGR (4.19 ± 0.40), and 7 T SSGR + SPIR (4.31 ± 0.48 ; Figs. 3, 8). However, only for SSGR + SPIR, the homogeneity improvement over the clinical reference image was finally statistically significant (Table 4). Regarding the delineation between 2 different (adjacent) structures, statistical analysis revealed sequence-specific differences as follows ($P < 0.05$, corrected for multiple comparisons, Table 4). For fat versus muscle, 7 T SSGR (4.94 ± 0.25) as well as 7 T SSGR + SPIR (5.00 ± 0.00) yielded a superior delineation compared with 3 T SPAIR (3.00 ± 0.00), 7 T SPIR (3.00 ± 0.00), and 7 T SPAIR (3.38 ± 0.50 ; all $P \leq 0.001$). For cartilage versus fat, 7 T SPAIR (4.00 ± 0.00), 7 T SSGR (4.75 ± 0.45), and 7 T SSGR + SPIR (5.00 ± 0.00) yielded a superior delineation in contrast to 3 T SPAIR (3.06 ± 0.25) and 7 T SPIR (2.94 ± 0.44), whereas 7 T SSGR and 7 T SSGR + SPIR provided better performance compared with 7 T SPIR and 7 T SPAIR (all $P \leq 0.001$). With respect to the contrast fluid versus fat, no significant between-sequence differences were found (ratings for all sequences were between 4.94 and 5.00; all $P > 0.05$). Regarding the contrast fluid versus cartilage, 7 T SSGR (4.88 ± 0.34) and 7 T SSGR + SPIR (4.88 ± 0.34)

yielded superior performance compared with 3 T SPAIR (4.00 ± 0.00), 7 T SPIR (4.00 ± 0.00), and 7 T SPAIR (4.00 ± 0.00 ; all $P \leq 0.001$). For the contrast cartilage versus bone, analysis demonstrated better delineation for 7 T SSGR + SPIR (5.00 ± 0.00) compared with 3 T SPAIR (4.13 ± 0.34), 7 T SPIR (4.00 ± 0.00), 7 T SPAIR (4.00 ± 0.00), and 7 T SSGR (4.06 ± 0.44 ; all $P \leq 0.001$). Finally, for the contrast cartilage versus cartilage, 7 T SPIR (2.81 ± 0.40) was lower compared with 3 T SPAIR (4.19 ± 1.11 ; $P = 0.003$). However, 7 T SPAIR (3.63 ± 0.50), 7 T SSGR (4.13 ± 0.62), and 7 T SSGR + SPIR (4.75 ± 0.45) yielded similar contrast compared with 3 T SPAIR ($P = 0.069$ – 0.915). At 7 T, SPIR was inferior to SPAIR, SSGR, and SSGR + SPIR (all $P \leq 0.001$) for the delineation of cartilage versus cartilage.

DISCUSSION

The SSGR method provided a strong and homogenous fat suppression for clinical knee imaging at 7 T. Quantitatively no significant differences in the grade of fat suppression was found between SSGR and SSGR + SPIR, but SSGR + SPIR yielded qualitatively better images in terms of strength and homogeneity of fat suppression compared with SSGR as assessed by 2 independent radiologists. Compared with standard spectrally selective suppression methods at 3 T, the SSGR technique can provide better image quality, either as a stand-alone method or in combination with SPIR fat suppression.

The SSGR method has several advantages such as efficient use of scan time, and it does not introduce additional SAR.^{16,22} These 2 advantages are of crucial importance at 7 T imaging because of the inherently longer relaxation times of tissues causing long acquisition times hence hampering the clinical use. Specific absorption rate limitations are also a frequent problem at high-field and ultra-high-field strengths, especially when fat suppression is needed. Thus, low SAR sequences are desired or, at least, techniques should not further increase SAR. However, SAR is very difficult to measure on a sequence-per-sequence basis, and no direct SAR comparison of different fat suppression techniques that would have included the SSGR technique is reported in the literature. Nagy et al have first described the SSGR technique and mentioned that their technique could reduce SAR compared with STIR and SPIR, if used as a standalone technique since no additional RF pulses are needed.¹⁵ In our study, we used a combination of SSGR + SPIR, and it was performing

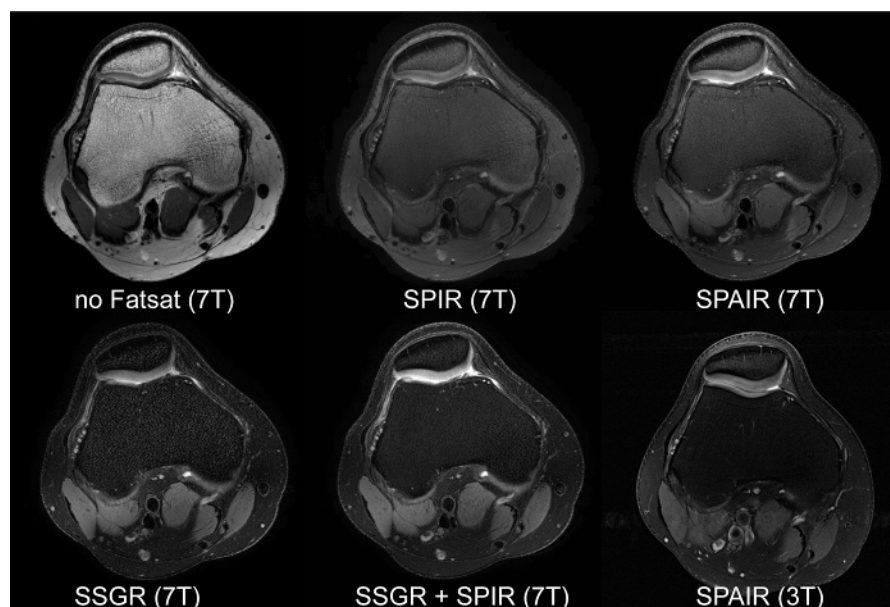


FIGURE 3. Series of acquired images in vivo of one volunteer at both field strengths.

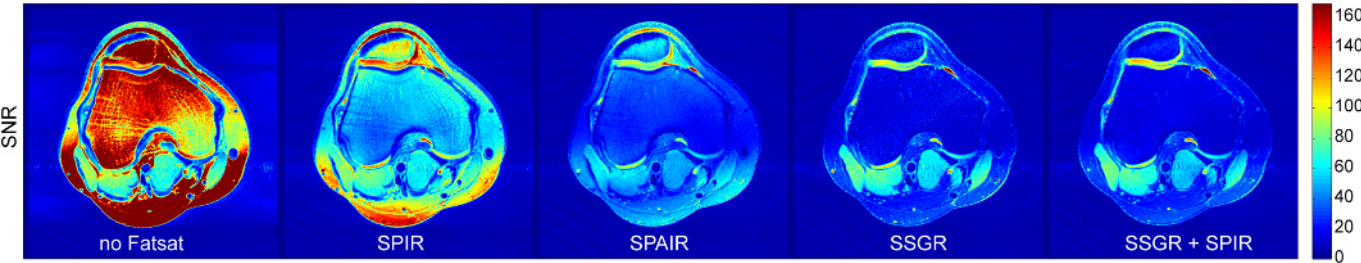


FIGURE 4. Corresponding SNR maps of the same volunteers as in Figure 3 show that, in SSGR + SPIR, the fat suppression is more homogenous and stronger compared with the other techniques at 7 T.

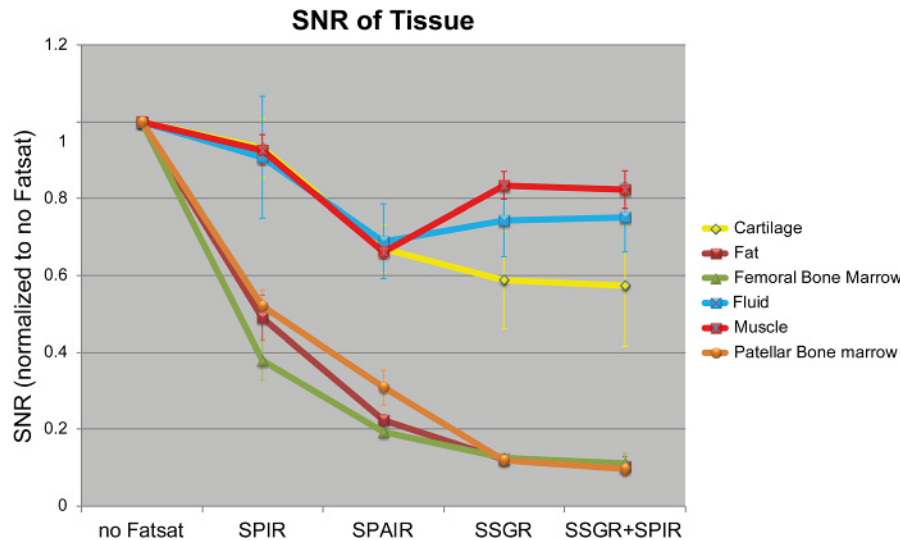


FIGURE 5. Chart shows a decline of SNR of various fat containing tissues with different fat suppression techniques at 7 T, whereas tissues without or with only little fat are hardly affected, except for cartilage.

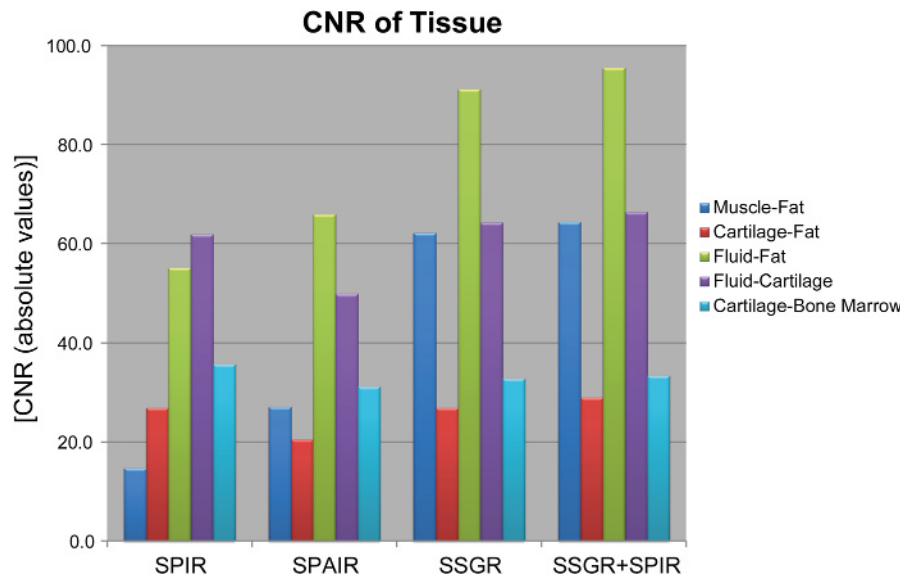


FIGURE 6. Bar charts show absolute CNR values of various tissues with different fat suppression techniques at 7 T.

TABLE 3. Statistical Analysis Using Paired Sample *t* tests of the CNR Analysis at 7 T

	CNR				
	Muscle vs Fat	Cartilage vs Fat	Fluid vs Fat	Fluid vs Cartilage	Cartilage vs Bone Marrow
SPIR vs SPAIR	0.015*	0.723	0.104	0.001*	0.664
SPIR vs SSGR	≤0.001*	0.855	0.006*	0.800	0.867
SPIR vs SSGR + SPIR	≤0.001*	0.757	0.006*	0.548	0.902
SPAIR vs SSGR	≤0.001*	0.089	0.001*	0.091	0.649
SPAIR vs SSGR + SPIR	≤0.001*	≤0.001*	0.002*	0.038*	0.659
SSGR vs SSGR + SPIR	0.091	0.565	0.236	0.0374	0.864

All numbers are *P* values.

*Statistical significance at a given alpha level of 0.05.

CNR indicates contrast-to-noise ratio; SPIR, spectral presaturation with inversion recovery; SPAIR, spectral adiabatic inversion recovery; SSGR, slice-selective gradient reversal.

TABLE 4. Qualitative Analysis of 3 T and 7 T Images

A: Pooled Results of Both Readers for the Qualitative Analysis for Image Quality, Grade of Fat Suppression, and Homogeneity of Fat Suppression as well as for the Delineation Between 2 Adjacent Structures and the Corresponding Interreader Agreement (Cohen κ)

	3 T SPAIR		7 T SPIR		7 T SPAIR		7 T SSGR		7 T SSGR + SPIR		Cohen κ
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Image quality	3.94	0.44	5.00	0.00	5.00	0.00	5.00	0.00	4.81	0.40	0.86
Grade of fat suppression	3.94	0.25	2.00	0.00	3.00	0.00	4.06	0.25	5.00	0.00	0.947
Homogeneity of fat suppression	3.94	0.44	3.69	0.48	4.00	0.00	4.19	0.40	4.31	0.48	0.87
Delineation of structures											
Fat vs muscle	3.00	0.00	3.00	0.00	3.38	0.50	4.94	0.25	5.00	0.00	0.94
Cartilage vs fat	3.06	0.25	2.94	0.44	4.00	0.00	4.75	0.45	5.00	0.00	0.92
Fluid vs fat	5.00	0.00	4.94	0.25	5.00	0.00	4.94	0.25	5.00	0.00	0.87
Fluid vs cartilage	4.00	0.00	4.00	0.00	4.00	0.00	4.88	0.34	4.88	0.34	1.00
Cartilage vs bone	4.13	0.34	4.00	0.00	4.00	0.00	4.06	0.44	5.00	0.00	0.96
Cartilage vs cartilage	4.19	1.11	2.81	0.40	3.63	0.50	4.13	0.62	4.75	0.45	0.86

B: Statistical Analysis Using Paired Sample *t* Tests of the Qualitative Analysis

	Image Quality	Grade of Fat Suppression	Homogeneity of Fat Suppression	Delineation						
				Fat vs Muscle	Cartilage vs Fat	Fluid vs Fat	Fluid vs Cartilage	Cartilage vs Bone	Cartilage vs Cartilage	
<i>P</i>										
3 T vs 7 T										
3 T vs SPIR	≤0.001	≤0.001	0.102	1.000	0.157	0.317	1.000	0.157		0.003
3 T vs SPAIR	≤0.001	≤0.001	0.564	0.014	≤0.001	1.000	1.000	0.157		0.107
3 T vs SSGR	≤0.001	0.157	0.102	≤0.001	≤0.001	0.317	≤0.001	0.705		0.915
3 T vs SSGR + SPIR	≤0.001	≤0.001	0.014	≤0.001	≤0.001	1.000	≤0.001	≤0.001		0.069
7 T										
SPIR vs SPAIR	1.000	≤0.001	0.025	0.014	≤0.001	0.317	1.000	1.000		≤0.001
SPIR vs SSGR	1.000	≤0.001	0.011	≤0.001	≤0.001	1.000	≤0.001	0.564		≤0.001
SPIR vs SSGR + SPIR	0.083	≤0.001	0.015	≤0.001	≤0.001	0.317	≤0.001	≤0.001		≤0.001
SPAIR vs SSGR	1.000	≤0.001	0.083	≤0.001	0.001	0.317	≤0.001	0.564		0.005
SPAIR vs SSGR + SPIR	0.083	≤0.001	0.025	≤0.001	≤0.001	1.000	≤0.001	≤0.001		0.001
SSGR vs SSGR + SPIR	0.083	≤0.001	0.157	0.317	0.046	0.317	1.000	≤0.001		0.008

SPAIR indicates spectral adiabatic inversion recovery; SPIR, spectral presaturation with inversion recovery; SSGR, slice-selective gradient reversal.

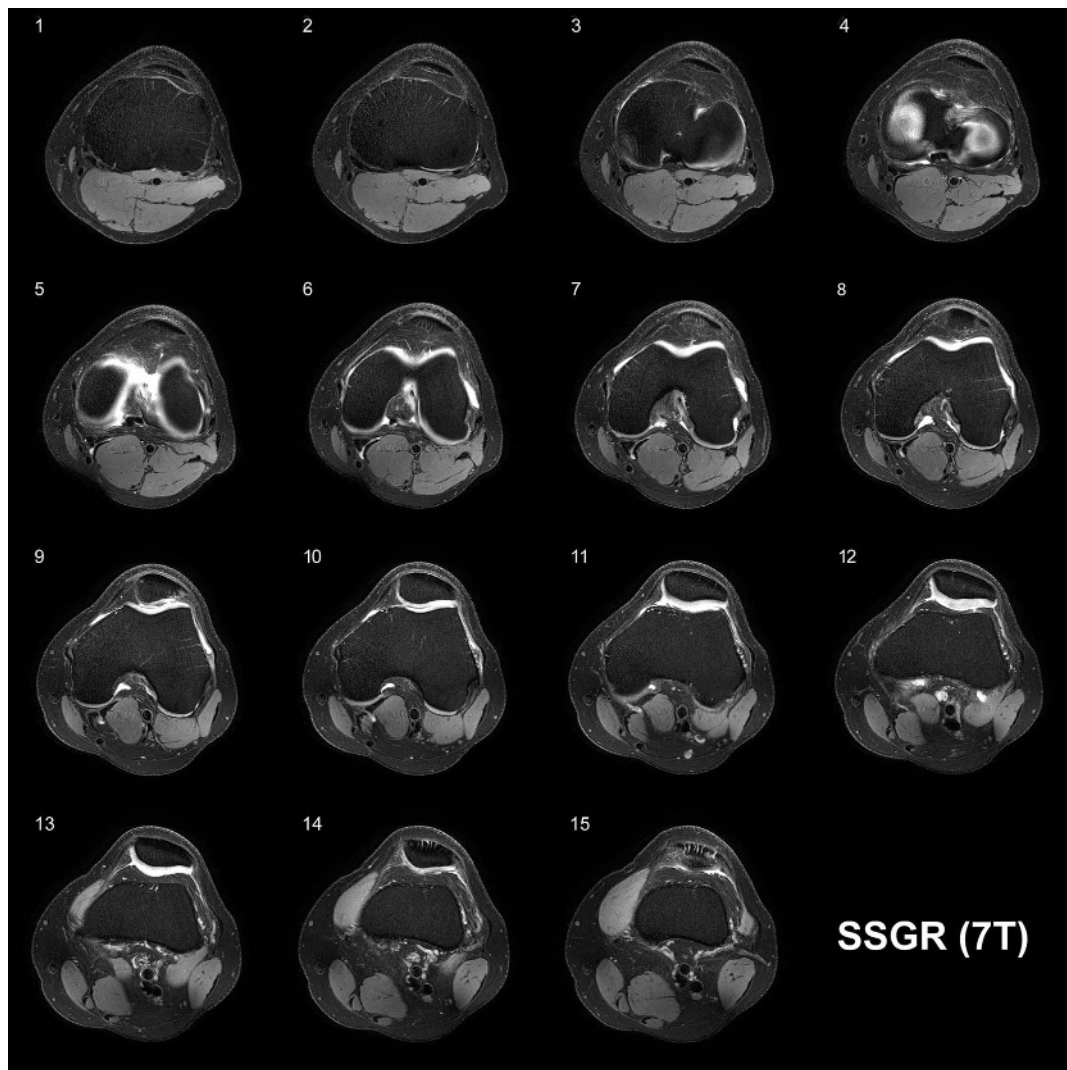


FIGURE 7. Series of all acquired axial sections using SSGR at 7 T of one volunteer showing that the proposed technique is robustly working in the full field of view.

better than the standalone version. Concerning the SAR, there is no difference if SPIR is used standalone or in combination of SSGR + SPIR because, according to Nagy et al, the SSGR technique does not add additional SAR. As a side note, a typical clinical knee MRI protocol contains not only one fat suppressed sequence (as tested here in our study), but several sequences in different planes.^{3,14} Hence, any SAR saving effect will multiply in the clinical routine.

One potential disadvantage of the SSGR method might be the completeness of the fat suppression. In some cases, the grade of fat suppression could be perceived as too strong by the radiologist. As shown, the achieved fat suppression reaches more than 85%. Some of the vendors thereof offer different “fat suppression strengths” in their scanner user interfaces, where the operator can then choose from, for example, “weak,” “medium,” and “strong” fat suppression strengths. This should be kept in mind when the grade of fat suppression is discussed. However, most radiologists prefer a very high homogeneity of fat suppression, and this was achieved using the combination of SSGR + SPIR. Inhomogeneous fat suppression is considered a lack of image quality and may hamper diagnostic accuracy.¹⁴ Another potential disadvantage of the SSGR technique might be the loss of SNR in water containing structures such as cartilage. In our study, we found a significant loss

of SNR regarding cartilage. However, the CNR was much less affected, and this was reflected by the qualitative evaluation where both radiologists did not observe an insufficient delineation of anatomical structure, that is, cartilage.

Because the SSGR-based method suppresses any off-resonance signal, caused by, for example, B0 field inhomogeneity, it requires a spatially homogeneous magnetic field.^{15,16} At 7 T, susceptibility effects are more pronounced than on lower-field strengths. In pretests, we found that around the patellar region, image quality in terms of fat suppression and SNR was unsatisfactory for a possible clinical use. To avoid water suppression, for example, of retropatellar cartilage tissue, large susceptibility differences need to be addressed, for example, by placing susceptibility matched material on top of the knee around the patella. We therefore used Fomblin oil that is based on fluorine, which is a suitable substance for this purpose because it has the same susceptibility as water but does not produce any signal in ¹H MRI.¹⁸

Our study has limitations. First, our cohort is small; we only included 8 human subjects, which were all volunteers. This may hamper the strength of conclusions. In addition, no patients could be included, because the used 7 T system has no approval for patient use by the local ethical board regulations at its current setting. Larger studies on patients

All Volunteers SSGR + SPIR (7T)

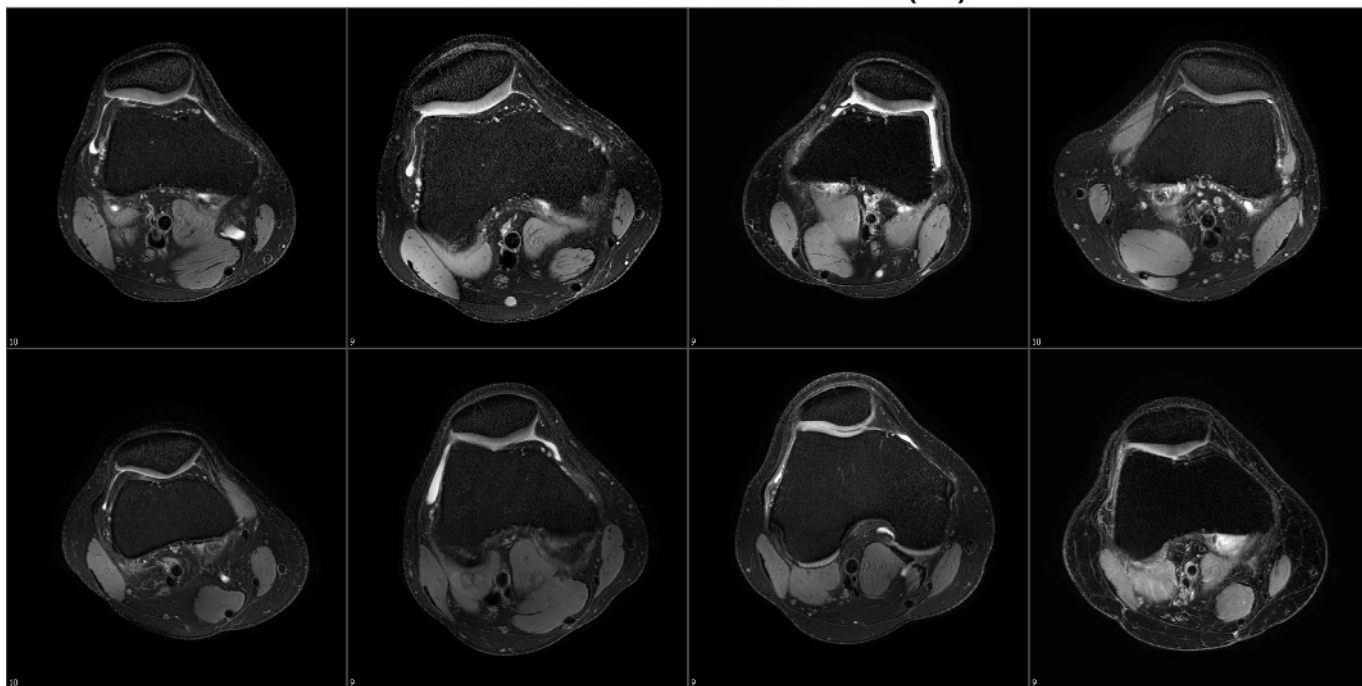


FIGURE 8. Series of axial MRI scans of all 8 volunteers shows the consistency of the SSGR + SPIR technique for the whole cohort at 7 T for the whole cohort.

are needed in the future. Second, scanners from different vendors were used (Siemens for 3 T and Philips for 7 T). However, on both systems, a dedicated transmit-receive knee coil from the same coil manufacturer (QED) with similar coil design and hardware components was used. We used a standard pulse sequence available on both scanners and kept all sequence parameters identical except for the fat suppression technique. On the 7 T system, this included preparation parameters usually not reported (eg, receiver gain settings, f0 determination, RF power optimization, and shimming). Third, for this study, we used soft cushions filled with Fomblin oil.¹⁸ It is not approved as a medical product and cannot be used in clinical routine. According to our personal experience, Fomblin oil is well suited to reduce susceptibility effects at tissue-air interfaces.¹⁸ Currently, we are not aware of approved alternative products on the market, which sought to achieve similar effects. Last, SAR was not measured in this study, because there is no reliable and standardized approach.

CONCLUSIONS

At 7 T, fat saturation for clinical knee imaging using SSGR and the combination of SSGR and SPIR was superior compared with standard methods based on spectrally selective RF pulses.

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